Environmental Characteristics of Convective Systems During TRMM-LBA

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ABSTRACT

In this paper, data collected from 51 days of continual upper atmospheric soundings and the TOGA radar at ABRACOS Hill during the TRMM-LBA experiment are used to describe the mean thermodynamic and kinematic airmass properties of wet season convection over Rondonia, Brazil. Distinct multi-day easterly and westerly lower tropospheric wind regimes occurred during the campaign with contrasting airmass characteristics. Westerly wind periods featured modest CAPE (1000 J kg^{-1}), moist conditions (>90% RH) extending through 700 mb and shallow (900 mb) speed shear on the order of 10^{-4} s^{-1}. This combination of characteristics promoted convective systems that featured a relatively large fraction of stratiform rainfall and weak convection nearly devoid of lightning. In contrast, easterly regime convective systems were more strongly electrified and featured larger convective rain rates and reduced stratiform rainfall fraction. These systems formed in an environment with larger CAPE (1500 J kg^{-1}), drier lower and middle level humidities (< 80% RH) and a wind shear layer that was both stronger (10^{-3} s^{-1}) and deeper (700 mb).

The time series of low- and mid-level averaged humidity exhibited marked variability between westerly and easterly regimes and was characterized by low frequency (i.e. multi-day to weekly) variations. In addition to its importance in stratiform rain formation, the humidity content directly influenced cloud cover, and thus the degree of thermal instability present during regimes. The synoptic scale origins of these moisture fluctuations are examined. The results reported herein provide an environmental context for ongoing dual Doppler analyses and numerical modeling case studies of individual TRMM-LBA convective systems.

1. INTRODUCTION

The Tropical Rainfall Measurement Mission (TRMM) component of the Brazilian Large Scale Biosphere-Atmosphere (LBA) experiment (hereafter referred to as TRMM-LBA) was conducted during January-February, 1999 to measure the dynamical, microphysical and environmental properties of mesoscale convective systems (MCS) during the wet season in Rondonia, Brazil. Numerous squall-type MCSs were sampled during this period, in which the regional-scale airmass conditions fluctuated between westerly and easterly wind regimes (Silva Dias et al., 2001). These periods are defined in terms of the direction of low-level wind prevailing for periods of several days to a week or more. The synoptic origins of wind regimes during TRMM-LBA are discussed in Rickenbach et al. (2001) and Petersen et al. (2001). Rickenbach et al. (2001) also found that the rainfall characteristics of these two regimes differ markedly in terms of their convective vs. stratiform rain fractions. In that study, eastward-propagating MCS were more oceanic in character and featured relatively weak convection (Cifelli t al., 2001) and a larger fraction of rainfall incident from extensive stratiform cloud. Westward-propagating squall lines, in constrast, derived more of their total rainfall from deeper and more intense leading-edge convection (Rickenbach et al., 2001; Cifelli et al., 2001). The electrical properties of westerly vs. easterly MCS were also shown to strongly contrast, whereby easterly systems were significantly more electrified than their westerly counterparts (Williams et al., 2001). Similar regimes have been identified in other regions of the tropics, such as the Darwin, Australia region (Rutledge et al., 1992; Williams et al., 1992) and classified there as monsoon and break.

While Betts et al. (2001) discuss the TRMM-LBA boundary layer thermodynamics and fluxes in terms of regimes, the primary objective of this paper is to describe the deep column thermodynamic and kinematic properties and their association with general convective morphology. Environmental parameters examined here include measures of stability such as convective available potential energy (CAPE) and convective inhibition (CIN), the structure of vertical shear profiles and the vertical distribution of column water vapor. The thermodynamics and shear demonstrate regime-dependent constrasts which play an important role in modulating the general properties of TRMM-LBA MCSs. Rickenbach et al. (2001) found that the easterly flow periods are established by the subtropical Atlantic ridge, while low-level westerly flow arises from stationary frontal systems extending into the deep tropics along the South Atlantic Convergence Zone (SACZ). An additional important objective of this paper address the large-scale origins of the moisture variability attending these circulation changes. Evidence will be presented that variations in column moisture content result from differences in both low level and mid level air trajectories. To a large extent, the moisture varilability in turn controls the thermodynamic stability in terms of CAPE and CIN. The overarching goal of the paper is to provide a descriptive physical context for ongoing, detailed observational and modeling studies of individual MCSs during TRMM-LBA.

This paper is organized as follows. Section 2 describes the various measurement systems and limitations of the data. Section 3 presents a synopsis of mean squall system properties as a function of the five identified low-level wind periods. In Section 4, key airmass properties are related to daily rainfall values and are presented in the form of regime-averaged quantities and vertical profiles. The origins of these properties and their hypothesized influence on squall system behavior is also discussed. Section 5 details specific synoptic-scale controls on airmass moisture variations. A summary of these results and concluding remarks are given in Section 6.

2. DATA AND METHODS

a. *Upper Air Soundings*

The primary data for these studies were obtained from a mesoscale network of four radiosondes located in the vicinity of Ji Parana, Rondonia. The soundings sampled basic state variables at three-hourly intervals near continuously for a 51 day period, from January 9 through February 28. This period included two occurrences of westerly, two instances of easterly and one weak zonal wind regime. The array, shown in Figure 1, consisted of two types of sounding systems: Vaisala RS-80 radiosondes launched from Rolim de Moura and Rebio Jaru sites, and VIZ Mark II radiosondes released from ABRACOS Hill and Rancho Grande sites. Both vendors' instruments provided a 1-mb (or smaller) vertical sampling interval for pressure, temperature, relative humidity (RH), windspeed and direction. Global Position System (GPS) windfinding techniques were utilized in both systems. Published accuracies of the VIZ and Vaisala radiosondes under ideal conditions (i.e. perfect launch procedures, no bias and no turbulent variability) are as follows: Temperature +/- 0.2 °C; pressure +/- 0.5 mb; relative humidity +/- 2%; and winds +/- 0.5 m s^{-1}. Coordinated radiosonde releases were nominally made every three hours at the sites; however, logistical issues periodically reduced the launch frequency to six-hourly, and also led to a multi-day shutdown of one of the sites (Rancho Grande) in the middle of the campaign.

For the purposes of this study we present upper air sounding data for the ABRACOS Hill site only. Observations collected there represent the longest and most complete record of the four sites. As of publication, quality control issues concerning the ABRACOS radiosondes remain, with analysis efforts ongoing in both the United States and Brazil. The data quality issues pertain to random errors in *individual* sounding temperature and humidity, as well as a systematic biases with respect to relative humidity (Zipser and Johnson, 1998). To date, we have identified a mean RH bias of 5-10% between VIZ and Vaisala sondes. In addition, there is also frequent occurrence of random errors in the ABRACOS sounding temperature and humidity with RMS values of 1.4 °C and 2.8 g kg^{-1}, respectively (Roy and Halverson, 2001). In this study, the sonde data were examined only in terms of mean vertical profiles averaged over many days, and also using smoothed time series analysis techniques. These procedures should have removed much of the random error component, while preserving *relative* changes in mean profiles representative of the various regimes. Our contention is that meaningful signals can be extracted which appear reasonable in the context of regime-averaged MCS properties and the larger scale forcing. It is important to note that when the time-series averaged humidity at ABRACOS is compared with similar analyses at the other three sounding sites, the results yield equivalent trends aside from known systematic offsets in RH.

b. *TOGA Radar and Lightning Measurements*

Summary rainfall statistics for each regime were generated from 10-min, 1 km x 1 km cartesian maps of radar reflectivity generated by the Tropical Oceans Global Atmosphere (TOGA) C-band (5 cm) radar located adjacent to ABRACOS Hill at Ouro Preto, Brazil. The NASA TOGA completed a full volume scan every 10 min out to a range of 150 km. Reflectivity data were corrected for calibration errors and removal of all non-meteorological echo and second trip echo was performed (Anagnatsou et al., 2001; Rickenbach et al., 2001). These data were then converted to rainfall rate (Tokay et al., 2001), and partitioned into convective and stratiform raining regions (Steiner et al., 1995; Rickenbach and Rutledge, 1998). The computed summary statistics in Section 3 include mean convective and stratiform rain rates (mm hr^{-1}) and percentage of stratiform rainfall. Regime-averaged statistics were computed for all precipitating features within the radar field of view, including the effects of both small, transient convective cells and the larger organized MCSs. In addition to multi-day regime averages, daily averaged, area integrated rain rates were generated. Trends in the evolution of these rain metrics are correlated with changes in the upper tropospheric thermodynamics in Section 4.

Information on lightning activity was provided by field change antennae equipped with flat plate electrodes (Rust and MacGorman, 1987; Williams et al., 1992) at ABRACOS Hill. The nominal detection range is on the order of 30-40 km radius within the larger envelope of TOGA radar coverage and included detections of both cloud-to-ground and intra-cloud discharges. The measure of MCS electrical activity used in this paper is the daily absolute peak flash rate (PFR) and reported as flashes per minute (fpm), which has been correlated with TRMM-LBA convective vigor and vertical structure (Williams et al., 2001).

3. CHARACTERISTCS OF TRMM-LBA CONVECTIVE SYSTEMS

A general description of the precipitation, electrical and morphological properties of rain-producing systems for each of the five regime occurrences is now presented. More specific details on rainfall and lightning characteristics can be found in Rickenbach et al. (2001) and Williams et al. (2001). A total of twenty five MCSs were identified during TRMM-LBA, with the predominant form of organization being linear i.e. most of the MCSs examined featured a discrete convective line with a variable degree of stratiform organization trailing or surrounding the convection. Organized convective were identified through subjective examination of the lowest tilt (0.5 deg) reflectivity maps generated by the TOGA radar at ten minute intervals, with range extending to 150 km. Regions with locally high reflectivity (> 30 dBZ) and/or large reflectivity gradient were used to distinguish between convective and stratiform precipitation. The criteria used in this study to identify a linear MCS include: 1) convective organization, broken or continuous, that extends along a line for at least 100 km; and 2) systems that maintain a coherent linear architecture for at least three hours.

Table 1 relates the bulk (i.e. regime-averaged) characteristics of TRMM-LBA rain systems to wind regime. The horizontal structure and evolution of a typical MCS sampled from each regime are also shown in Figure 2. Here, regimes have been defined according to the predominant direction of the lower (< 3 km) tropospheric u-wind component based on a height-time section analysis of the ABRACOS wind data (Figure 4), consistent with the synoptic-scale evolution of flow fields described in Rickenbach et al. (2001). Of the five regime occurrences presented in the table (two westerly, two easterly and one weak zonal), only a single organized convective line was noted during the first westerly regime (WLY1, January 11-19) while as many as nine lines occurred during the second easterly regime (ELY2, February 9-22). Also shown in Table 1 are the orientations of the linear portions of MCSs and the frequency of specific orientation occurrence. In most cases, convective lines tended to be perpendicular (within 30 deg) to the prevailing lower tropospheric zonal wind (Barnes and Sieckman, 1984; Weisman and Klemp, 1986; Keenan and Carbone, 1992; Garstang et al., 1994; LeMone et al., 1998). During weak zonal conditions (WKZON, January 27-February 8), the regime-averaged u-wind component was light and variable below 3 km, and MCS motion was determined primarily by a persistent low-level northerly current.

The daily maximum peak flash rate (PFR) varied considerably, ranging from zero flashes per minute (fpm) in the second westerly regime (WLY2, February 23-28) to a maximum of thirty fpm during the first easterly regime (ELY1, January 20-26). The maximum PFR values that occurred in each regime instance are shown in Table 1, and individual daily values are shown along the top panel of Figure 3b. No data were obtained during the weak zonal regime because of problems encountered in the operation of equipment. It appears that convective systems occurring during ELY1 were the most strongly electrified of all those in the experiment, and ELY2 regime convection was marginally more electrified than the first westerly period.

Mean convective rainfall rates for the easterly regimes (1.9 mm hr^{-1} for ELY1 and 1.4 mm hr^{-1} for ELY2) were nearly twice that of the two westerly regimes (0.8 mm hr^{-1}) with the weak zonal regime ranking intermediate. Stratiform rain rate was remarkably invariant (0.6 mm hr^{-1}) across all five regime instances sampled. However, the percentage of regime total rainfall associated with stratiform processes varied considerably between easterly and westerly conditions: 44-46% of the rainfall in westerly MCSs was stratiform, while only 24-

30% of easterly system rainfall was classified as stratiform in nature. The hypothesized reasons for this variation will be discussed in Sections 4 and 5.

The maximum horizontal extent (line perpendicular direction) of the stratiform rain shield varied widely during the experiment, ranging from 40 km to 230 km. At least one MCS with a trailing stratiform region exceeding 150 km width occurred in every regime occurence. In all five regime periods, stratiform rain (weak echo) was sometimes observed in the form of narrow ribbons or "streamers" projecting behind leading convection. Similar appearing structures were identified by Halverson et al. (1999) and LeMone et al. (1999). In LBA systems these features possibly resulted from the opposing motion of convective line propagation versus upper level zonal flow which was frequently 180 degrees out of phase (c.f. figures 2b and 2f, and discussed further in Section 4 below). However, there were also seven instances of MCSs with relatively narrow stratiform shields (e.g. 50 km wide or less), or a narrow band of short-lived stratiform that formed as a convective line decayed. All of these cases occurred during or within a few days of ELY2 from February 9 through February 23. In these storms, stratiform rain developed as a result of rapid *in situ* decay of a narrow convective line, rather than following the classic evolution whereby a long-lived and slowly expanding shield trails the leading edge convection. An example of these "weak stratiform cases" is shown in Figures 2d and 2e. Possible reasons for this class of storm morphology are discussed in Section 4.

Based on the results of Table 1, a consensus view of easterly regime MCSs emerges in which the convective component of rainfall and the frequency of lightning is larger than under westerly flow conditions. However, there are noteworthy differences in properties *between* ELY1 and ELY2. In general, the ELY1 systems were the most convectively vigorous of the entire experiment according to the following characteristics: 1) the PFR values exceeded 25 fpm on three out of seven days during ELY1, while no PFR value exceeded 14 flashes per minute during the entire fourteen day period of ELY2; 2) the mean convective rainrate during ELY1 was 26% larger than during ELY2; and 3) the smallest stratiform rain fraction (24%) of the five regime occurrences was noted during ELY1. The specific mechanisms responsible for these differences are explored in the next two sections.

4. ENVIRONMENTAL PROPERTIES OF TRMM-LBA MCSs BY REGIME

The relationship between daily integrated rainfall as measured by the TOGA radar and the ABRACOS thermodynamic environment is shown in Figure 3. Shown are time series analyses of (a) 24-hour conditional rain rates (where the term *conditional* implies an average applied over the radar domain, only where raining); (b) lower tropospheric (1000-700 mb) layer mean relative humidity; (c) convective available potential energy (CAPE); and (d) convective inhibition (CIN). In panels b, c and d, the trend line plotted across individual 3-hourly values (computed from running averages) is indicated by a heavy solid line. The specific method used to compute CAPE and CIN is now described.

Convective available potential energy (CAPE) and convective inhibition (CIN) values were calculated for the ABRACOS Hill soundings by lifting a parcel with mean lower 500 m properties to the level of free convection and then to equilibrium level, following the standard pseudoadiabatic process (and ignoring ice processes). The averaged CAPE and CIN values were computed only for daytime and nocturnal conditions that were considered undisturbed. Categorization of soundings into disturbed and undisturbed classes was made by subjectively examining each sounding's structure combined with radar analyses and field observations recorded at launch time. The undisturbed category contained those conditions which were 1) clearly pre-convective with a well-mixed and dry adiabatic boundary layer; 2) were not released during precipitation of any intensity; and 3) were not launched in the immediate hours following passage of an intense MCS. The undisturbed sounding sample represents 67% of the total population of soundings (n=281) used in the analysis.

This comparative time series analyses in Figure 3 highlight a relationship between variations in daily rainfall intensity and contrasting regime thermodynamics. The strongest coincidences between airmass properties and rainfall are most notable during the two easterly periods (ELY1 and ELY2). The largest daily averaged rain rates (exceeding 1.5 mm/hr) occured during these two periods (January 20-26 and February 7-23). There was a correpsonding increase in CAPE, with maximum values at or exceeding 1500 J kg^{-1} during the rainfall maxima, and also an increase in convective inhibition to values greater than 20 J kg^{-1}. Relative mimima in CAPE (~1000 J kg^{-1} or less) and CIN (< 20 J kg^{-1}) correspond to periods of reduced daily rain rate, namely the westerly wind regimes at the beginning and end of the experiment and the zonally neutral regime between ELY1 and ELY2. During easterly flow conditions there was also an abrupt drying of the lower troposphere, manifested by a decrease in 1000-700 mb RH from 90% or greater to about 80%. Figure 3 thus illustrates important changes in airmass properties which accompany shifts in the direction of prevailing winds, and the correlation of these changes with daily storm rainfall.

Table 2 illustrates bulk airmass thermodynamic and kinematic properties in the form of regime averages. As documented in Section 3, easterly flow convection was more vigorous than its westerly counterpart, both in terms of electrical activity and amount of rain generated by the convective line. The metrics presented in Table 2 offer several possible mechanisms. First, the available thermodynamic energy in the form of CAPE is on the order of 50% larger for the easterly cases, and convective inhibition is roughly twice that of the westerly regime. Reasons for the larger CAPE and CIN are apparent from examination of Figure 4, which shows mean thermodynamic soundings constructed for the easterly and westerly regimes based on the subset of undisturbed soundings. The composites were constructed using 91 soundings for the two easterly regimes and 40 for the two westerly ones. CAPE is uniformly larger throughout the entire parcel ascent path during easterly periods and the positive energy area extends through a deeper layer of troposphere. A uniform increase in CAPE is attributable to a 2-3 K increase in boundary layer temperature and steeper lapse rates below 750 mb. Lapse rates are identical above 750 mb for both regimes. The more energetic boundary layer results from reduced cloud cover (Betts et al., 2001) and prevailing drier lower and middle tropospheric humidities.

Convective inhibition is also larger during the easterly regime. The larger CIN arises within the first 1.5 km of the atmosphere and serves to weakly “cap” growing thermals early in the afternoon. This may increase updraft vigor once clouds erupt into the LFC (Carlson and Farrell, 1982).. We note that explosive deep convective growth commonly commenced around 15 UTC or 11 am LST during TRMM LBA. We hypothesize that the combined effects of increased CAPE and CIN promote stronger updrafts leading to greater upward flux of moisture and thereby invigorated the mixed phase region, increasing production of both rainfall and enhancing electrical charge separation (Zipser, 1994; Zipser and Lutz, 1994; Williams et al, 2001). We also note that the mean environmental sounding for all neutral regime days is virtually identical to the mean westerly sounding shown in Fig. 4.

A second mechanism favoring stronger easterly flow convection may be due to the presence of deeper and stronger lower tropospheric wind shear. The magnitude of the vertical shear was determined for the 0-3 km layer based on regime-averaged vertical profiles of u- and v- winds. During TRMM LBA this layer captured the most significant variation of wind structure in the lower and middle troposphere. A factor of 2 to 3.5 times increase in the lower layer shear strength (Table 2) is noted for the easterly regime. Figure 5 shows a height-time section of zonal wind component for the entire TRMM-LBA experiment. The corresponding regime-averaged vertical profiles of u- and v-wind components are shown in Figure 6. The u-wind profiles for ELY1 and ELY2 are nearly identical and both exhibit a deep low-level speed maximum of about 5-6 m s^{-1} near 3 km (700 mb). The v-wind profiles, while generally weaker, feature a northerly maximum near 3 km. In contrast, sheared flow during westerly conditions was much shallower in both u and v, with the wind maximum located at the top of the boundary layer (1 km). Below 500 mb, the mean wind profile for the weak zonal regime generally mimicks westerly flow conditions but the more significant shear is contained in the meridional component.

It is has been theorized that a stronger and deeper layer shear structure strengthens the vigor of updrafts through several mechanims. The shear promotes a larger relative inflow of unstable air into developing cells, and moves these cells away (downshear) from the stable cool pool/ouflow (Moncrief and Green, 1972; Weisman and Klemp, 1986). Furthermore, tilting of the updraft mitigates the adverse effects of water loading on updraft buoyancy (Browning, 1986). The tilted low-mid level updrafts in a characteristic LBA easterly flow MCS were shown to be a factor of two larger than that for a westerly regime system featuring erect low-mid level updrafts (Cifelli et al. 2001). The stronger updraft in the easterly case resulted in higher maximum 30 dBZ echo heights, which has been correlated with larger rainfall production (DeMott and Rutledge, 1998a).

The wind profiles shown here are virtually identical to those found in a study of monsoon and break convective regimes over Darwin, Australia (Keenan and Carbone; 1989, 1992). Airmass characteristics of the Darwin monsoon (oceanic) versus break (continental) periods and attendant MCS properties are similar to the Rondonian westerly and easterly regimes, respectively. Figure 1 of Keenan and Carbone (1989, not shown) shows the mean vertical wind structures for these two regimes, with a moderate, 3-km deep easterly shear (10^{-3} s^{1}) prevailing during break conditions. During the Darwin monsoon period, the westerly shear layer was much shallower (1 km) and weaker (10^{-4} s^{-1}). It is also worthwhile to note that both CAPE and CIN were larger during the Darwin break versus monsoon, similar in both respects to the differences between Rondonian easterly and westerly thermodynamic environments.

A third reason for differences between regime easterly and westerly MCS rainfall properties may be understood in terms of the highly variable moisture content of the column. Table 2 depicts layer-mean relative humidity values at ABRACOS Hill computed for two specific layers: Lower troposphere (1000-700 mb) averaged, and middle troposphere (700-300 mb) averaged humidities. Below 700 mb notably drier average ambient conditions prevailed during easterly flow. The reduction in available moisture during easterly periods, while still sufficient to support intense deep convection, may have promoted smaller stratiform region rain fractions (24-30% for easterly MCS vs. 44-46% for westerly MCS) through increased evaporation of hydrometeors generated within stratiform cloud. The precipitation efficiency of MCS-generated nimbostratus has been shown to be highly sensitive to column precipitable water (Ferrier et al., 1996). Cloud resolving model simulations using the Goddard Cumulus Ensemble (GCE) model (Tao et al. 1993) as well as observations from the TOGA Coupled Ocean Atmosphere Response Experiment (COARE) (Halverson et al., 1999) also suggest that decreases in middle tropospheric humidity are accompanied by reductions in both the areal coverage of stratiform rainfall and its contribution to the storm-total rainfall amount. Further discussion on the origin of these humidity variations will be presented in Section 5.

Differences between the intensity of ELY1 and ELY2 regime convection were noted in Section 3. As Table 2 shows, the magnitude of both CAPE and vertical shear are very similar between these two regimes. However, the larger PFR values and 26% larger convective rain fraction of ELY1 systems may be attributed to a 40% increase in CIN during this regime. The effect of CIN is to trap or concentrate low level energy (both by delaying the onset of convection, which allows insolation to increase the boundary instability; and also by preventing the instability from being released everywhere) which, when released, enhances the updrafts that do develop (Fulks, 1951; Carlson and Farrel, 1982). Greater solar heating was also associated with reduced cloudiness during ELY1 (Betts et al., 2001). The surface values of theta were obtained from the University of Virginia microflux tower which provided 1-min averaged measurements and was located adjacent to the ABRACOS Hill sounding release site (Betts et al., 2001). The ELY1 theta value of 306.0 K was 1.5 K larger than the surface value observed during ELY2. Furthermore, the direction of prevailing upper level winds was in the same direction as MCS motion during ELY2; thus there is the possibility of precipitation falling into inflow air, with attendant reduction in available instability. Finally, deep convection growing into drier average mid level conditions during ELY2 may have been more hindered by the effects of dry entrainment.

Finally, it was noted that several MCS occurring during the ELY2 period featured very small (or virtually nonexistent) stratiform rain regions. These "weak stratiform" cases include seven MCS events during the five-day period from February 7- 23. Two possible explanations are offered for this anomaly. First, the identified MCSs tended to cluster around the time of absolute minimum middle (700-300 mb) and lower (1000-700 mb) tropospheric relative humidity ~ 55% RH during the experiment (the times of these MCS are denoted by an "X" in Figure 7, Section 5). Enhanced evaporation in this very dry environment would further constrain the horizontal growth of extensive stratiform cloud layers. The second reason is due to the orientation of the prevailing winds with respect to MCS motion. During the WLY1, WLY2 and ELY1 regimes, Figure 5 shows that the convective line motion opposed the direction of middle and upper tropospheric winds i.e. a reversing shear profile prevailed. Such a shear would enhance the horizontal expansion of stratiform cloud from its generating convective source. However, during the ELY2 regime, the line motion and upper level flow are directed in the same sense – limiting the horizontal spread of nimbostratus cloud layers. In Figure 5 the time of the weak-stratiform events have been plotted with an "X".

5. SYNOPTIC ORIGINS OF MOISTURE VARIATIONS BETWEEN REGIMES

As shown, one of the apparent cofactors associated with more widespread rainfall in the westerly regimes is larger ambient moisture content in the lower troposphere. As shown in Table 2, there was significant inter-regime modulation of humidity. Figure 7 presents a time series analysis of relative humidity at ABRACOS Hill for the entire TRMM-LBA campaign. Temporal changes are expressed as mean humidities averaged with respect to two layers: 1000-700 mb (lower troposphere) and 700-300 mb (middle troposphere). The thin tracing in Figure 7 shows the instantaneous (i.e. three-hourly) humidity values from individual soundings, whereas the heavy dashed line indicates a 30-point running average (essentially a four-day filter). This smoothed analysis reveals pronounced, low-frequency trends in the humidity behavior. It should be noted that this same analysis carried out at the three other network sounding sites (not shown) reveals very similar patterns of humidity variation.

In general, lower atmospheric conditions were substantially drier during the two easterly wind regimes, averaging about 80% relative humidity and 90% or higher under westerly conditions. Occurrences where the RH exceeds 90% may partly reflect a moist bias characteristic of the VIZ radiosonde moisture sensor (Zipser and Johnson, 1998). However, the *relative* difference in humidity between regime occurrences is preserved no matter which of the four LBA sounding sites is examined. The zonally weak period between ELY1 and ELY2 was also moister throughout the column. We note that the degree of humidity variation in the upper troposphere (100-300 mb) remained very small throughout the experiment and is therefore not discussed in detail.

Changes in middle level humidity with respect to wind regime are not as well defined. Trends in middle level moisture do not phase well with those below 700 mb. The exception is during the first half of ELY2, where the driest conditions in the lower and middle troposphere coincide. Note that between February 5-8, the 1000-700 mb layer was very moist (90% RH) while the middle levels were very dry (55% RH). Also, the driest low-level conditions during ELY1 occurred early in this period (January 20) while the driest middle level conditions did not occur until a week later (January 27). During this seven day period, the low levels underwent steady moistening while the middle levels experienced gradual drying. This behavior implies that processes leading to moisture changes in these two layers are likely independent of one another.

An examination of NASA Data Assimilation Office (DAO) averaged synoptic wind fields for easterly vs. westerly periods provides insight into one possible mechanism responsible for modulating the lower tropospheric humidity. Figure 8a and 8b shows the 850 mb wind composites averaged for westerly and easterly periods, respectively, during TRMM-LBA. During westerly flow, the subtropical anticyclone was positioned southeast of South America. This resulted in a broadly recurving flow across northern Brazil, with the airmass originating over the tropical Atlantic. Near-equatorial easterlies were deflected by the Andes and forced to cross the equator, entering Rondonia as a northwesterly current. This Atlantic ocean source flow thus experienced a long, uninterrupted fetch over moist rain forest canopy. Fluxes of water vapor from the wet season forest (due to evapotranspiration) can lead to substantial moistening of the boundary layer and promote large mixing ratios (Martin et al., 1988). This would act to maintain the high humidity content of the Atlantic source air against convective rainout, and possibly upwards through several kilometers through the action of both dry and moist convective mixing.

In the easterly regime composite (Figure 8b) the flow associated with the subtropical anticyclone is more zonal, occuring as a broad easterly current directed westward across most of Brazil. Importantly, there is no recurvature of easterlies across the northern country, and as a consequence the trajectory of air across Rondonia is considerably shortened. Furthermore, this airmass now traverses the semi-arid Brazilian Highlands east of Rondonia. A combination of sparse or non-existent rain forest canopy, semi-aridity (the Highlands to the east of Rondonia receive average annual rainfall of less than 2000 mm, compared to greater than 4000 mm in the interior forest north of Rondonia [Sombroek, 1999]) and gradual downsloping of air along the western face of the Highlands (terrain relief ~ 1000 m) should promote drying. Interestingly, once this drier low level air enters Rondonia, there is a steady increase in low layer moisture content in the days following its arrival (e.g. moistening trend noted after January 18 and February 11, Figure 7). This may reflect progressive modification of the dry air as it moves over a convectively active region (Rondonia); the airmass is moistened through the daily action of locally generated rainfall (and that generated immediately upstream) and evapotranspiration off the forest canopy.

We now direct our attention to the issue of middle level humidity variation. An examination of synoptic-scale patterns of humidity across much of Brazil was facilitated by Geostationary Observatory Environmental Satellite (GOES) imagery depicting the middle-trospospheric water vapor channel (6.7 μm). Successive half-hourly images were animated to observe changes in moisture throughout the entire experiment. As Figure 7b shows, there are two key periods of interest, namely drying of the 700-300 mb layer between January 18-27 and February 2-14. Such drying may have been induced by westward migration of meso-synoptic-scale, upper-level cyclones. These cyclones are regularly occurring features during the wet season and are associated with upper level convergence and suppression of convection on their western side (Kousky and Gan, 1981). The migration of these vortices was implicated as a reason for the transient reversal of upper-level meridional winds over Rondonia during the TRMM-LBA (Rickenbach et al., 2001).

Figure 9a shows a sequence of moisture channel images for the period 22-26 January. Images at 00 Z (left column) and 12 Z (right column) on each day are both shown, so that the evolution of upper level features can be traced during the convectively active portion of the diurnal cycle (00Z) and the suppressed early morning period (12 Z). By following the red arrow in this image we note that a weak upper level cyclone and its associated tongue of dry air advects in from the east. The western edge arrives at the TRMM LBA site (heavy yellow circle) by 26 January. From Figure 7b note that the minimum mid-level RH also occurred on January 26. The green arrow in Figure 9b points to a second, smaller and less well defined cyclone which also advects dry air into the TRMM-LBA region around 24-25 January. Several soundings in the LBA network echoed the arrival of the upper level vortex early on January 26. Subsidence induced drying and warming was pronounced in the middle layers of these soundings This suppressed convective line activity moving into the network. While it is slightly difficult to identify the center of rotation of the vortices in static images such as those shown in Fig. 9, animation of the frames more clearly depicts the cyclonic rotation and translation of these subtle upper level features.

A more pronounced drying of the 700-300 mb layer occured during early February. Figure 9b shows a more robust example of a westward propagating upper level cyclone during this period (red arrows). The swirl of dry air associated with this feature arrived at the TRMM-LBA site by 12 Z Feb 4, in good agreement with the drying trend noted in Figure 7b during 1-5 February. One item to note, though, is that the cyclones appeared to weaken and lose definition on each successive day. As the cyclones translate westward, it is likely that the dry air contained within their cores was gradually moistened by repeated episodes of afternoon and evening convection.

We hypothesize that the drying of the middle layers in response to these cyclones exerts a marked effect on the convective system morphology within easterly regimes. On the one hand, the reduction in middle and upper level cloudiness permitted stronger solar heating, leading to greater instability and stronger updrafts. On the other hand, the drier mid-level environment promoted enhanced evaporation and sublimation of moisture in the MCSs that did develop, diminishing both the areal coverage of stratiform cloud and also the stratiform rainfall fraction. As the results in Section 3 show, both of these impacts were observed in the summary statistics (Table 1 and Table 2) that characterized the easterly regime systems.

6. SUMMARY AND CONCLUSIONS

In this paper, data collected from 51 days of continuous upper air soundings at ABRACOS Hill during TRMM-LBA were used to describe the general thermodynamic and kinematic airmass properties of wet season convection over Rondonia, Brazil. As presented in this study and in others, convective properties were found to contrast significantly between periods dominated by lower tropospheric easterlies versus lower tropospheric westerlies. Westerly regime rain systems featured mean convective rain rates that were half the magnitude of those in easterly systems, and the fraction of stratiform rainfall generated was nearly twice as large for westerly disturbances. Daily values of the PFR were 4-5 times greater under easterly flow conditions than in the westerly regime (Williams et al., 2001).

The time series of daily-averaged conditional rain rates was well correlated with changes in airmass CAPE, CIN and lower tropospheric humidity. Bulk thermodynamic properties from the ABRACOS soundings averaged according to regime show that the westerly periods had a mean CAPE of around 1000 J kg^{-1} and high humidity (> 90%) in the lower half of the troposphere. Mostly cloudy to completely overcast conditions prevailed, interspersed by weakly organized convective lines, reducing the insolation and leading to lower CAPE. Mean shear profiles indicated a shallow westerly speed maximum near 900 mb but the shear was weak, on the order of 10^{-4} s^{-1}. These conditions were remarkably similar to the monsoon convective regime described for the Darwin, Australia region in 1987-1988 (Keenan and Carbone, 1992). In both Australia and Brazil, the high moisture, moderate CAPE and low windshear conditions appeared to promote convective systems which produce large fractions of stratiform rainfall and weak convection nearly devoid of lightning (Cifelli et al., 2001; Williams et al., 1992).

In contrast, the convective environment during TRMM-LBA easterly regimes was one in which partly cloudy to sunny skies prevailed, punctuated by vigorous afternoon squall lines that were often strongly electrified. The mean airmass properties featured larger CAPE (1500 J kg^{-1}), drier lower and middle level humidities and a wind shear layer that was both stronger (10^{-3} s^{-1}) and deeper (700 mb). The lower unstable boundary layer air was also weakly capped in the 1-2 km layer, which may have enhanced the release of instability. More intense low-mid level updrafts were observed in easterly regime convection (Cifelli et al., 2001) which we hypothesize are a direct consequence of greater instability and a deeper, stronger shear. A reduced stratiform rainfall fraction present in these systems resulted from enhanced evaporation of precipitation into a drier subcloud environment. Marked reduction in the dimensions of stratiform raining area during the second easterly regime also likely resulted from weakened upper tropospheric winds, which limited the horizontal spread of condensate from the convective portion of mesoscale lines. Both the convective system properties and convective environments of TRMM-LBA easterly regime storms strongly parallel those for the Darwin, Australia continental break period (Cifelli and Rutledge, 1994).

The column humidity in the environment of convection varied markedly between westerly and easterly regimes in the manner of low frequency (i.e. multi-day to weekly) oscillations. We hypothesize that alternating periods of drying and moistening in the lower levels (1000-700 mb) were the result of different surface trajectories undertaken by Atlantic Ocean source air. Under westerly flow conditions, blocking of low level flow by the Andes forced the air to recurve across a broad fetch of Amazon rain forest. Evapotranspiration of moisture during this air trajectory's long passage over dense forest canopy maintained the oceanic airmass moisture content against depletion from rainout and contributed to large relative humidities. During the easterly periods, the air trajectory shifted to a straight-in easterly flow off the Atlantic. Before arriving in Rondonia, the oceanic air traverses a broad region of highlands devoid of rich forest cover and one which is substantially more arid than the Rondonian rain forest. The drier nature of the surface combined with broad downsloping of the airmass as it settled westward may have promoted drying of the lowest few kilometers.

Trends in lower and middle level humidity content occasionally coincided, i.e. dry conditions prevailed through a deep layer (300 mb) on several days during both easterly regimes. However, the trends were also frequently decoupled. One explanation for middle level dry episodes was that they arose from the action of westward-moving upper-level cyclonic vortices featuring subsidence on their western flanks. The timing of these dry air intrusions was such that they occasionally coincided with episodes of lower tropospheric easterlies, and the entire column thus experienced a marked reduction in water vapor. During February 11-14, for instance, total column humidity was at its absolute minimum (i.e. 30% RH in mid-levels), and several of the squall lines that developed during this time produced very little stratiform rain.

This investigation provides a context for the general environmental forcing of cloud systems in ongoing dual-Doppler analyses (Cifelli et al., 2001) and numerical modeling case studies (Tao et al., 2001). Cloud resolving model (CRM) experiments can clarify the relative importance of environmental parameters discussed here such as shear strength vs. CAPE during the different TRMM-LBA convective regimes. In addition, significant mesoscale variations among moisture and winds were often present *within* the TRMM-LBA sounding network. An understanding of these gradients is just as important as the mean differences between regimes and may play an equal role in defining the wide variety of convective morphology observed during the Rondonian wet season.

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9. Figure Captions

Figure 1. Location of TRMM LBA sounding network and TOGA radar at ABRACOS Hill, Ji Parana, Rondonia, Brazil. Triangles denote the mesoscale sounding network. Solid concentric circle surrounding the TOGA radar site is the 150 range ring.

Figure 2. TOGA radar 2 km CAPPI reflectivity images showing orientation, movement, evolution and morphology of typical MCS during various wind regimes. Two images for each MCS are shown to illustrate the system evolution. White arrows indicate direction of MCS propagation. Radius of radar coverage extends 150 km. Color scale ranges from low reflectivity values (blue) to high (red).

Figure 3. Relationship between (a) daily averaged conditional rain rate (mm hr^{-1}) integrated over the area of TOGA radar coverage and (b) – (d) thermodynamic quantities derived from the ABRACOS Hill soundings. Field mill PFR values (flashes per minute, maximum observed in the 24 hour period) are shown by staggered gray numbers across the panel top; (b) three-hourly layer-mean relative humidity values for all levels between 700-1000 mb; (c) individual three-hourly values of CAPE (J kg^{-1}), derived from a 500-m averaged parcel for undisturbed soundings; and (d) individual values of CIN (J kg^{-1}), again computed from a 500-m averaged parcel for undisturbed soundings. Solid curves drawn through individual data points reflect a running average of all values.

Figure 4. Regime-averaged soundings at ABRACOS Hill for (a) mean westerly conditions and (b) mean easterly conditions.

Figure 5. Height time analysis of sounding u-wind component at ABRACOS Hill. The X's denote time of occurrence of MCSs featuring small or absent stratiform regions. Warm colors (yellow and red) denote westerly flow; cold colors (blue and violet) indicate easterlies. Color fill intervals are every 2.5 m/s. Solid white line separates regions of easterly and westerly flow. Black arrows show general direction of MCS propagation during regimes (i.e. from the east, west or north).

Figure 6. Mean u- and v-wind profiles constructed from ABRACOS Hill sondes during five occurences of lower tropospheric wind regimes.

Figure 7. Time series of layer-averaged relative humidity from ABRACOS Hill radiosondes for (a) lower troposphere (1000-700 mb) and (b) middle troposphere (700-300 mb). X's denote time of occurrence of MCSs featuring small or absent stratiform regions.

Figure 8. Analyses of DAO 850 mb winds averaged for TRMM LBA (a) westerly regime composite and (b) easterly regime composite.

Figure 9. Sequence of GOES water vapor channel (6.7 μm) images during January 22-26 (a) and February 1-5 (b) showing the evolution of westward-propagating upper level cyclones and associated dry air. Yellow circle in each image denotes the location of the TRMM-LBA experimental network. Red and green arrows point to center of cyclonic vortices.